STUDIES ON THE DEVELOPMENT AND CONTROL OF COAL-DUST EXPLOSIONS IN MINES

BY IRVING HARTMANN

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by

Irving Hartmann[1/]

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SUMMARY

The Experimental Coal Mine of the Bureau of Mines has served principally as a valuable and unique testing laboratory for studies of the explosibility of coal dust and mine gas; studies of the numerous complex and interrelated chemical and physical factors that govern the ignition of coal dust and the propagation of mine explosions; and studies designed to develop measures for preventing explosions or reducing their destructive effects. These researches, coupled with educational efforts by the Bureau of Mines and enlightened safety consciousness in the mining industry, had fruitful results. This is evidenced by the remarkable reduction in the frequency of major coal-mine explosions and the number of fatalities from explosions since the Bureau of Mines was established.

Despite this progress, further important unresolved problems arise; these are due in part to changes in mining conditions and methods, which have brought about increased production of fine coal dust in highly mechanized operations. To solve the new problems, research must be continued without interruption. The results of many very recent and current studies in the Experimental Coal Mine are summarized briefly, and pertinent studies by European mine-safety-research organizations are listed.

INTRODUCTION

This report is based on a paper delivered by the author at the Second Annual Symposium on Mining Research, Missouri School of Mines and Metallurgy and the Federal Bureau of Mines, Rolla, Mo., November 13, 1956. The paper was given at the invitation of the organizer of the symposium, Prof. George B. Clark, Department of Mining Engineering, Missouri School of Mines and Metallurgy, Rolla.

During the last century investigators recognized that finely divided coal dust plays a role in many mine explosions; however, the full importance of coal dust was not realized until the Courrières explosion in France in 1907, when 1,100 men were killed. It did not become known until later that in widespread explosions coal dust is the principal, if not the only, flame-propagating combustible substance. During the first decade of the present century many serious mine explosions occurred in this country and abroad. These led to the opening of the Experimental Coal Mine soon after the Bureau of Mines was established in 1910; this marked the beginning of intensive research on mine explosions. The need for such research was great, because knowledge concerning explosions and safety standards in mines was primitive.

In 1910 most mine operators did not consider coal dust alone explosive in the absence of methane in the mine air, and little or no attempt was made to allay or to remove dust from mine workings. Ventilation in mines was poor, and small volumes of methane were disregarded. Many believed that improved ventilation aided the spread of coal-dust explosions, because it provided more oxygen at working faces. The introduction of permissible explosives had just begun, and black powder and dynamite generally were employed for blasting. No permissible electrical equipment was

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available, and open lights were used in many mines. The direction of the air current in mine entries was believed to have a marked influence on the propagation of explosions; and moisture and high atmospheric humidity were considered to be effective safeguards against explosions.

INVESTIGATIONS IN THE EXPERIMENTAL COAL MINE

Although explosion studies had been conducted in surface galleries in England and other European countries before the Experimental Coal Mine was opened, this mine provided the first underground testing laboratory in which carefully controlled, large-scale tests could be made under conditions simulating actual mining practices. The mine is at Bruceton in Allegheny County, Pa., about 13 miles southwest of Pittsburgh. It is developed by drift openings, 9 to 10 feet wide and 6 to 7 feet high, in the Pittsburgh bituminous-coal bed, which in this vicinity is essentially level, is 62 to 64 inches thick, and outcrops along the hillsides. There are two main headings, termed "entry" and "aircourse," which are 1,308 feet long; these and the other entries and rooms that have been driven as needed for experimental work are shown in figure 1. Points along the entry and aircourse, respectively, are designated by the letters E and A and a number, which represents the distance in feet from the mine portals. In the figure this system is used to designate a few of the rib stations in which instruments are housed for recording of explosion phenomena; E 1308 designates the face of the entry. The immediate roof stratum above the coal bed is a clayey shale, locally known as draw slate, which ordinarily is 6 to 10 inches thick.

The original objective of the Experimental Coal Mine was to serve as a place for testing the explosibility of coal dust and gases. It has, however, also been the scene of research on many other problems designed to promote safety in mining. These concern studies of mine- and vehicular-tunnel ventilation, mine-fire extinguishment, roof control, strength of mine stoppings, allaying of dust on roadways, compressibility of coal, helium storage, mine lighting, mine rescue training, and various investigations of explosives. The latter include research on deterioration of explosives in storage; generation of toxic gases during blasting; ignition of coal dust by permissible explosives; ignition of firedamp through fissures in coal; mudcap blasting; special stemmings; Hydrox, Chemecol, and other blasting devices; increase in charge limit from 1-1/2 to 3 pounds per shot hole; and millisecond-delay blasting.

To date about 2,500 explosion tests have been made in the mine. They were conducted chiefly in one or in both main headings, but many special tests were made in butt entries and in short, connected rooms off these entries. Single-entry tests were conducted in the main entry, which for this purpose was completely sealed off from the aircourse by explosion-proof stoppings. The 558-foot section from the face of the entry (E 1308) to E 750 is termed the test zone. This zone has a concrete floor, and the roof and sides are coated with a cement-sand mixture. This lining is used to facilitate cleaning after each test and to prevent dust that might be abraded from the coal bed from affecting test results.

Cross shelves 8 inches wide have been installed permanently about 1 foot below the roof at intervals throughout the test zone. In addition, 4 continuous shelves, each 3 inches wide, are attached longitudinally to each rib.

In most experiments the dust to be tested is distributed uniformly and divided equally on the cross shelves, side shelves, and floor (see fig. 2); in some tests the rock dust or the rock-dust - coal-dust mixture is distributed by machine. This

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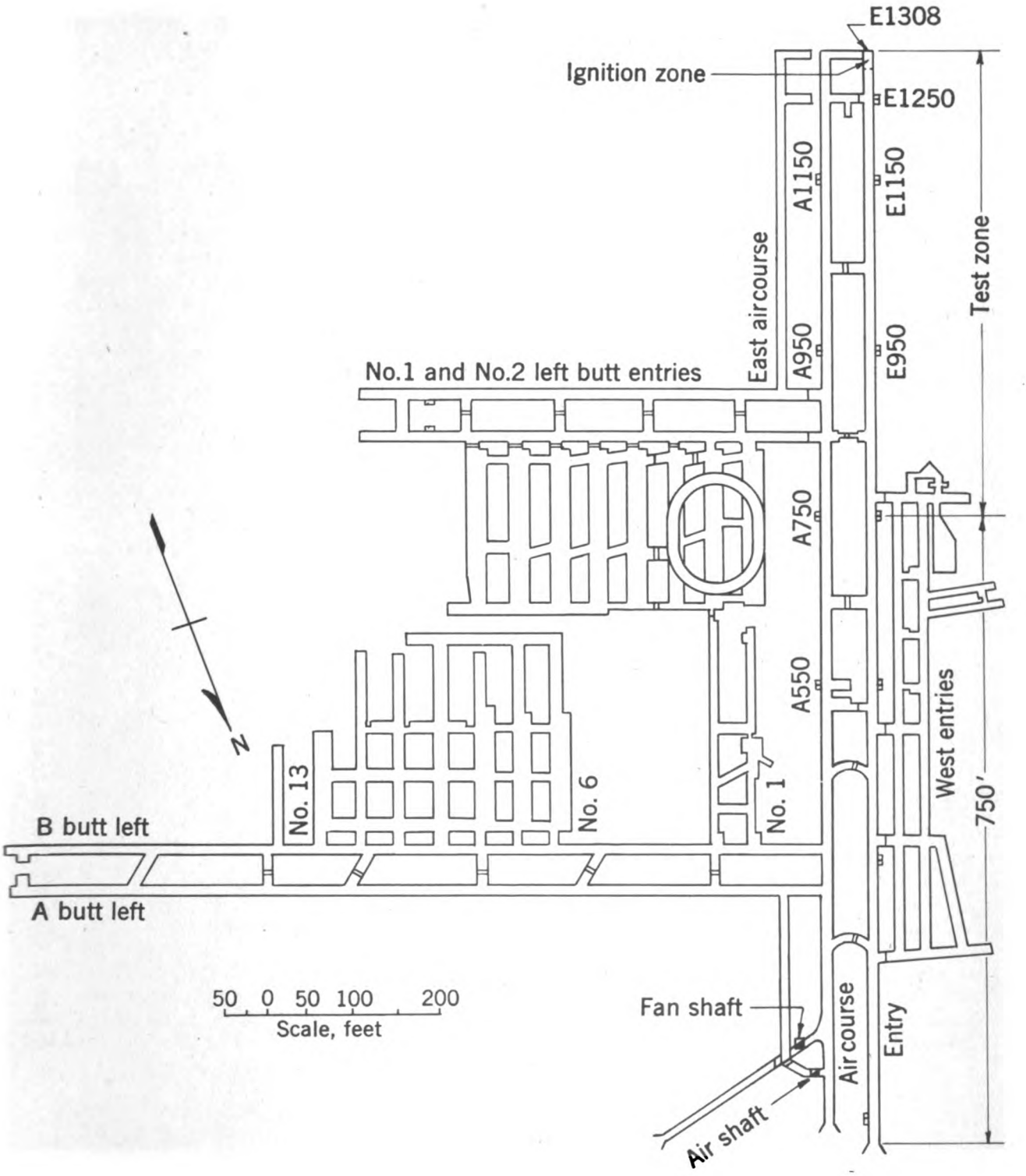

Figure 1. - Plan of Experimental Coal Mine.

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Figure 2. - Distribution of coal dust-limestone mixture in test zone of mine entry.

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distribution begins at E 1283, 25 feet from the face (or at E 1258), and extends to E 750; in some experiments shorter test zones are used.

In double-entry tests the crosscut at E 1250 is open. The dust is distributed from E 1258 to E 750, as in single-entry tests, and also in like manner through the open crosscut and in the aircourse to A 750.

The explosions are usually initiated in the 25- or 50-foot zone at the face of the entry; this is termed the ignition zone. In most tests 1 of 3 different igniting sources is used. The weakest source is a 5-ampere electric arc, over which 25 pounds of "pulverized" coal (75 to 80 percent through-200-mesh) is projected from a trough by compressed air; in addition, 100 pounds of pure pulverized coal is distributed in a 50-foot zone near the face. The second source consists of 1,300 cubic feet of 9- to 9.5-percent methane-air mixture in a 25-foot zone near the face of the entry; the gas mixture is ignited by an electric spark. The third source is a blown-out shot of 4 pounds of FFF black powder, fired from a steel cannon in the coal face into a 50-foot zone of 100 pounds of pulverized coal.

The chief purpose of the tests has been to study the ignition of coal dust and the initiation of explosions; observe the development of explosions and their propagation through the mine entry; study the general physical and chemical phenomena of explosions; and develop measures for preventing or controlling mine explosions. The tests were made under a wide variety of carefully controlled conditions. Measurements were made with electrically controlled instruments operated from an observatory on the surface to record the velocity and length of flame, the velocity of the shock wave preceding the flame, and pressures developed during the explosion. In many experiments information also was obtained on the nature and composition of the combustion products and the formation of coke in explosions. If, during a test, flame passed entirely through the zone containing the dust under test, the result was termed "propagation"; if the flame died out in the test zone the result was "nonpropagation."

Many tests were performed to evaluate the explosibility of coal dusts from various parts of the United States and from some foreign countries. In other tests mixtures of coal dust and limestone dust, shale, salt, and other inert dusts were used. The variables studied included the fineness of coal dust; the concentration of coal dust and its manner of distribution in the entry; the effect of low percentages of methane in the mine atmosphere; and the nature, fineness, and application of rock dust, etc. The coal dust used in most experiments was of so-called "mine size"; in this all particles pass through a No. 20 U. S. Standard sieve, and about 20 percent, by weight, are finer than a No. 200 sieve. In many other tests "pulverized" coal dust was used.

Factors Affecting Coal-Dust Explosions in Mines

Most of the Bureau's early studies of explosions have been published in various bulletins and reports. The work showed conclusively that coal dust without gas can produce widespread explosions; that under some conditions explosions can develop in relatively short, wide, connected rooms as well as in long, narrow entries; and that high atmospheric humidity and the direction of the ventilating current have little or no effect on propagation of explosions. It was learned also that the following physical and chemical factors have an important influence on the explosibility of coal dust and the control of explosions in mines:

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(1) Particle-size distribution of dust. - Coal dust as coarse as 20-mesh (830 microns) and, in some instances, even coarser dust may take part in mine explosions; but the fine particles control the ease of ignition, the violence, and the speed of flame propagation. Small dust particles constitute a greater explosion hazard because they are more readily dispersible, they remain in suspension longer, their greater surface in proportion to mass provides better contact with oxygen, and smaller particles are easier to ignite (see fig. 3). However, there appears to be a practical limit to the effect of fineness. Very fine particles tend to agglomerate; they may oxidize rapidly on initial exposure to air, and for some coals the less reactive portions of the coal are reduced in size more easily.

(2) Composition of dust. - The combustible volatile content of coal, related to its age and rank, has a most important effect on the explosibility of the dust. For low-volatile coals the explosibility increases almost linearly with increase in the volatile content, but above about 25 percent, in the range of medium- and high-volatile bituminous coals, the explosibility rises only slightly with increase in volatile content (see fig. 4). There are no records of dust explosions in coal mines working seams that contain less than about 10 percent volatile matter, but experimental explosions can be produced with dusts containing only 12 percent volatile, and mine explosions have occurred in seams working such low-volatile coals.

Of somewhat less importance are the ash and moisture content of the coal. Increase in these incombustible constituents is accompanied by reduction in the explosibility of the coal dust. Moisture has an inhibiting and cooling effect because energy is needed to heat and vaporize it, reducing the energy available for ignition of the dust cloud. Water vapor acts as an inert gas, diluting the atmosphere and reducing the percentage of oxygen in it. Moisture also tends to wet and agglomerate fine particles of coal dust, reducing their dispersibility. However, experiments have shown that much moisture is needed to actually prevent coal-dust explosions, and it is rare that dust can retain enough moisture in a mine so that reliance could be placed on it as an explosion-preventive measure (see fig. 5). When coal dust is insufficiently wetted, so that it can be dispersed into the air by a disturbance such as a blown-out shot or a gas explosion, tests showed that it will ignite and can propagate flame. A few of our worst explosions occurred in so-called "wet" mines.

(3) Flammable gas in air. - The presence of small percentages of natural gas in the air current (even well below its lower explosive limit of about 5 percent) was found to enhance the ease of ignition of coal dust and made it more difficult to arrest the explosion. The explosibility of coal dust, as measured by the proportion of incombustible dust required to stop flame propagation, was found to increase almost directly in proportion to the percentage of gas in the atmosphere (see fig. 4). Based on these findings, it has been recommended that for each 0.1 percent of gas the incombustible content of the mine dust should be increased by 1 percent above the required minimum of 65 percent.

(4) Quantity of dust. - The minimum explosive concentration of fine bituminous-coal dust in air was determined to be of the order of 0.05 oz. per cu. ft.; the exact value depends somewhat on the nature of the ignition source, the fineness of the dust, and other parameters. To propagate an explosion, at least this minimum quantity of dust must be suspended in air. Theoretically, the stoichiometric concentration of Pittsburgh-bed coal dust, the quantity that, if completely burned, would combine with all the oxygen in a cubic foot of air at normal temperature and pressure, is 0.118 ounce. This amount is equivalent to 7.4 ounces per linear foot of a mine entry 7 by 9 feet in cross section; uniformly distributed on the roof, ribs, and floor the dust would form a layer less than 0.01 inch thick. Actually the tests

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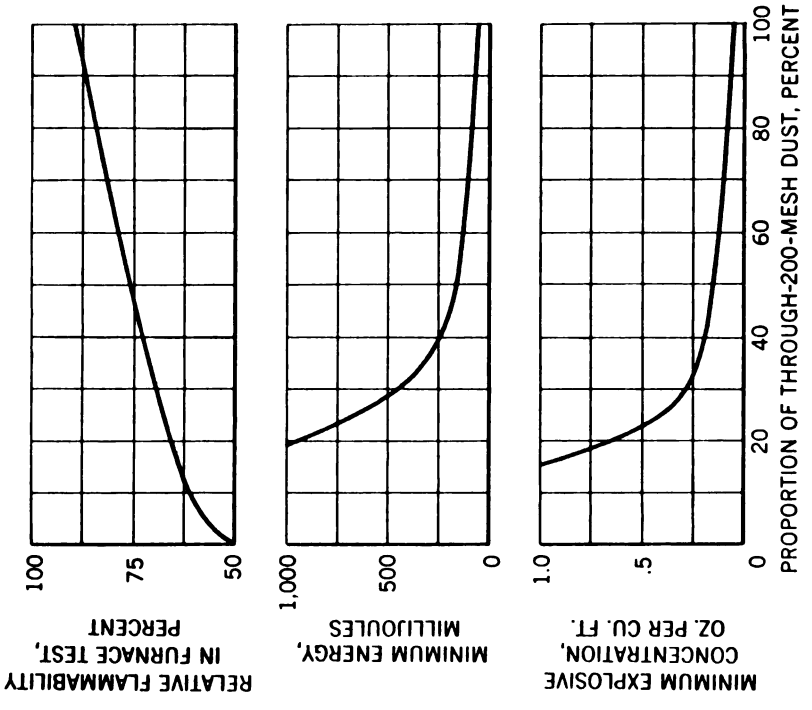

Figure 3. - Effect of various proportions of through 200-mesh particles in through 20-mesh dust on minimum explosive concentration, minimum igniting energy, and relative flammability of bituminous Pittsburgh-coal-dust clouds in air.

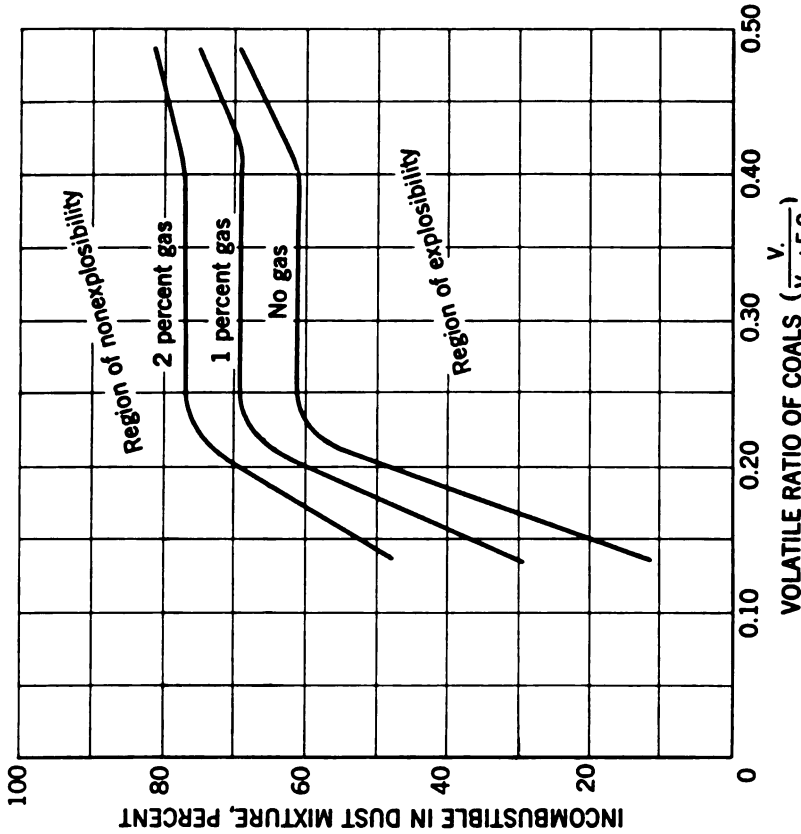

Figure 4. - Explosibility of mine-size coal dusts with and without gas in air current.

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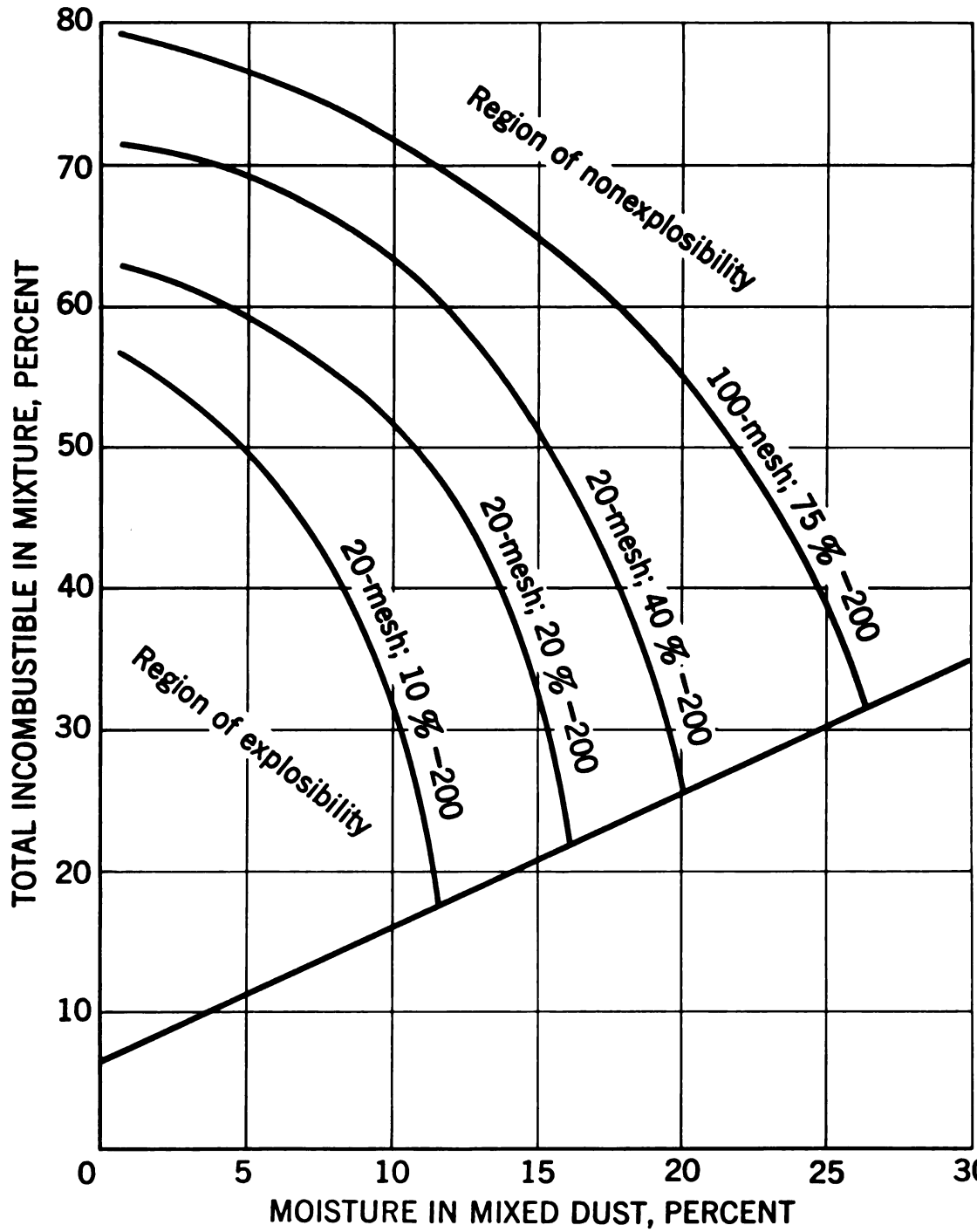

Figure 5. - Effect of moisture on explosibility of mixtures of Pittsburgh coal dust and rock dust.

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showed that the "optimum" concentration, at which maximum effects are produced by an explosion, is higher than the stoichiometric concentration. This is due in part to the fact that the time is so short during passage of an explosion flame that the coarser particles are only partly burned, and because at least part of the combustion takes place at higher than normal atmospheric pressure. The total amount of coal burned in an explosion is generally limited by the quantity of oxygen available.

(5) Distribution of dust in mines. - Coal dust is produced during cutting of the seam, drilling of shot holes, blasting, loading, haulage and other mining operations, as well as by spalling of coal ribs due to roof pressure. Some of this dust is transported by the air currents through the entries, where it is deposited on the ribs, roof, and floor. Unlike mine gas, which normally occurs only near active faces, in caved gob areas, and in limited volumes at other points in a mine, combustible coal dust may be present on all surfaces in sufficient quantity to propagate an explosion. The ease of dispersion and ignition of coal dust in air are markedly influenced by its original position along the perimeter of the mine entry. Coal dust deposited on rib and roof surfaces and on overhead timbers is generally of finer size, is more readily dispersible and ignitible, and constitutes a greater explosion hazard than coal dust on the floor. Once an explosion has developed, however, the forces are great enough to disperse considerable dust off the floor.

(6) Source of ignition. - The temperature, energy, and size of the source of ignition with relation to the volume of the dust cloud are important factors, in that they determine the dust-dispersing capacity, the turbulence induced within the cloud, and the igniting power of the source. Explosions initiated by strong sources develop faster, do more damage, and are more difficult to arrest than explosions initiated by weak sources. In a number of experiments when the explosion was permitted to develop initially in a non-rock-dusted (or otherwise protected) section of an entry 200 to 300 feet long, the explosion flame propagated through more than 1,000 feet of entries in which the incombustible content of the dust exceeded 65 percent.

The principal sources of ignition of mine explosions 40 to 50 years ago were open lights, and black powder and dynamite. In recent years electric arcs from trolley wires and from improperly maintained mining machines and power cables have become the chief hazard.

Causes of three recent major explosions. - Coal dust had an important part in 2 major explosions in Illinois, which resulted in a great number of fatalities, and in 1 recent major explosion in West Virginia. One major explosion in Illinois in 1947 was strictly a coal-dust explosion, in which coal dust was dispersed and ignited by explosives fired with cap and fuse in a dangerous and nonpermissible manner. The investigation showed that the coal dust was ignited either by a blown-out shot of explosives stemmed with coal dust or by an underburdened shot. A major explosion in Illinois in 1951 was caused by the emergence of a large body of explosive gas from an abandoned and caving area, resulting from the combined effect of caving and simultaneous short circuiting of the ventilating current through an open ventilation door. The gas was ignited by an electric arc or spark from nonpermissible electrical equipment. The explosion was propagated by coal dust and possibly by ignition of other bodies of gas in the mine. In a major West Virginia coal-mine explosion in 1954, the ignition was ascribed to blasting (coal-pillar stumps) in a nonpermissible manner of two or more charges of explosives in an explosive mixture of methane and air. Either flame of the explosive or an electric arc produced by short circuiting of the blasting wires (which were found connected to a 275-volt trailer cable of a shuttle car) was the igniting agent. Coal dust was largely responsible for the extensive spread of the explosion.

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(7) Surrounding conditions. - The size, shape, constrictions, obstructions, branching, and length, as well as the nature and condition of the surfaces of mine passageways through which an explosion propagates, affect the heat losses, turbulence, pressure piling, and venting in the explosion space and have an important influence on the development of a coal-dust explosion.

Much effort was directed in the Experimental coal-mine studies toward developing measures for preventing coal-dust explosions, as by the use of steam, by wetting coal dust, and by quenching with salt, limestone, shale, and other rock-dusting material. This research did much to convince the mining industry that rock dust is effective in stopping explosions, and this form of protection is now widely used in bituminous-coal and lignite mines. Rock-dust requirements for many coal fields were determined by large-scale mine tests and later by laboratory studies. The mine tests showed that all passageways of mines in producing areas should be rock-dusted to within 40 feet of the coal face, and the incombustible content of the mine dust should be maintained at 65 percent or more.

Other studies showed that explosion flames can be checked or extinguished by installing properly designed rock-dust barriers in mine passageways. However, such barriers were not adopted in American mining and were never advocated by the Bureau of Mines as a replacement for generalized rock dusting but rather to supplement rock dusting, especially to prevent the spread of explosions from one section of a mine to another. One reason for not using barriers is the fact that they require good maintenance to operate in case of an explosion. Germany is the only country in which rock-dust barriers have been adopted as a primary safeguard against explosions. Even there a certain amount of rock dust is distributed in addition to barriers. During the past few years barriers have been introduced in conveyor-belt entries in British coal mines, to supplement rock dusting and other explosion-preventive measures.

On the basis of the Bureau's studies of explosions, coupled with research by the United States Public Health Service, the present specifications for suitable rock dusts have been prepared. These require that 70 percent or more by weight of the dust particles be finer than 200-mesh; that the combustible content of rock dust should not exceed 5 percent; and that the total silica content should not exceed 5 percent. The specifications point out the desirability of using rock dusts of light color and indicate the need for rock dust to remain dispersible after application in mine workings.

Ignition of Dust Clouds and Development of Explosions

To ignite a dust cloud a source of ignition requires a certain minimum energy that must be imparted, generally in the form of heat, to a large enough volume of the cloud at an adequate rate. According to the "thermal theory," ignition is effected when a dust mixture is heated until its oxidation produces heat more rapidly than it is lost to the surroundings. This is followed by continuous surface heating, which leads to visible ignition at some point. Thereafter, the flame is propagated by conduction of heat from the flame front to the neighboring layers of the dust-air mixture. There is evidence that radiation plays a role in the ignition of dust clouds. Experience with coal, sugar, and other organic substances containing combustible volatile matter at one time led investigators to consider all dust explosions as purely gas or vapor explosions. Support was given to this theory by the fact that the sensitivity of coal dust to ignition increases with increase in the volatile content. According to this view, the energy of the igniting source heats the dust particles, causing evolution of the volatile matter. This gas mixes with

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air and ignites, producing heat, which in turn ignites the solid particles. This is termed the "predistillation theory" of dust ignition. One objection against its acceptance is that the ignition temperature of some dusts, including coal dust, is lower than the ignition temperature of the gases evolved, for example, methane. Another objection is that the gases and some distilled vapor from some dusts are almost incombustible. Examples are cellulose and starch dusts, which evolve chiefly carbon dioxide and water vapor during initial heating. Present evidence appears to indicate that the combustion of coal dust is a heterogeneous reaction, being due in its initial stage to surface oxidation of the solid coal material and in a later stage to the combustion of the gaseous components, as well as combustion of the solid. The rate of reaction is determined in large part by diffusion of oxygen toward the surfaces of the dust particles.

As has been mentioned, the presence of a small percentage of methane in the mine air reduces the lower explosive limit of coal dust and increases its sensitivity to ignition. A partial explanation of these effects is that the gas in the air becomes mixed with the combustible gas distilled from the coal dust during the initial stage of ignition, and thereby an explosive concentration is reached more rapidly than with coal dust alone.

In certain respects dust explosions are similar to gas explosions; the similarity is more pronounced as the particle size of the dust decreases. As in the case of gas, to produce an explosion the dust must be mixed intimately with air or another supporter of combustion. Generally an external source of ignition is needed to initiate the explosive reaction in dust clouds, as in gas-air mixtures. Both fuel mixtures have lower and upper explosive limits, although the upper limits of dust-air mixtures are very indefinite. Explosions of limit mixtures are weak, and the strongest explosions are produced by dust clouds that have intermediate concentrations. During the initial stages of most dust explosions and of many gas explosions there is an induction or ignition lag period, which is sometimes attributed to initiation of a chain reaction. The energy developed by complete combustion of dust in a given volume of air is frequently greater than that developed by combustion of gas, and the maximum pressures in some dust explosions are higher than in gas explosions. The rates of pressure rise are, however, generally lower in dust than in gas explosions. This arises from the fact that even the smallest dust particles are composed of aggregates of many molecules, so that diffusion of oxygen to the reactive surface is necessarily much slower than in gas explosions.

Dust explosions are frequently more disastrous in their effects than gas explosions, partly because of their longer duration, which results in a greater total impulse, and partly because combustible dust is often widely distributed, either unavoidably as in coal mines or through lack of attention in industrial plants. Turbulence enhances mixing of oxygen with the dust particles and promotes thermal diffusion, causing stronger explosions; the effect is somewhat similar in the combustion of gas-air mixtures.

In experimental coal-dust explosions initiated by blown-out shots a compression wave, sometimes termed a "shock wave" but actually a pressure pulse, travels through the air of the entry at the velocity of sound. When no fuel is present in the entry, the pressure of the compression wave diminishes as it travels; attenuation is particularly marked at points where there is branching into other passageways. The sonic compression wave is capable of dispersing dust from the ribs, roof, and floor. If ignition of coal dust follows the initial compression wave, there is a rapid succession of air waves from the explosive combustion, accompanied by a bodily forward movement of the air as a column. These waves and forward movements continue as far

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as the coal-dust explosion propagates, stirring up the dust ahead of the flame. It is this forward movement, with its accompanying waves raising coal dust, that makes spread of a coal-dust explosion possible. When a coal-dust explosion is initiated by a gas ignition or by an electric arc, there is no strong initial compression wave, and the pressure wave preceding the flame comes from combustion of the coal dust. As the flame travels, it not only premixes but preheats and precompresses the coal dust and air ahead of it, thereby increasing the rate of combustion and accelerating the violence of the explosion.

Whereas the velocity of the sonic compression wave is nearly constant, the initial flame velocity in coal-dust explosions is slow. Time is needed to disperse the dust, mix it in proper proportions with air, drive off some of the volatile constituents, and bring about actual ignition. The lowest flame velocity recorded in a self-sustained dust explosion in the Experimental Coal Mine was 30 feet per second; more commonly, the minimum velocities range from 50 to 100 feet per second. Unless the explosion is checked near its point of initiation, the flame velocity increases rapidly and generally reaches 1,000 to 1,500 feet per second in less than 1 second. In many explosions flame velocities exceeding 3,000 feet per second have developed, and in a few tests velocities exceeding 6,000 feet per second were attained. If propagation occurs in a sufficient length of passageway, the flame overtakes the initial compression wave and proceeds through a dust cloud formed at the flame front by the pressure of the expanding gases of combustion, projecting its own wave far enough ahead to stir up the amount of coal dust necessary for propagating the explosion.

The shape of the flame in weak experimental explosions is generally pointed, with the point somewhere near the center of the passageway. The flame at the pointed portion is as much as 100 feet long, and combustion takes place over a length of 300 feet or more at any instant. In rapid explosions the flame front is broader and the length of flame shorter.

At the start of a coal-dust explosion pressures are low, of the order of 2 to 5 pounds per square inch, unless the source of ignition is exceptionally strong. Under favorable conditions pressure rises rapidly to 25 to 30 pounds per square inch in less than 1 second, and pressures of 60 to 70 pounds per square inch have been measured in many explosions with relatively pure coal dust. The highest pressure recorded in the mine tests was 127 pounds per square inch; this was obtained with pure dust of low-volatile bituminous coal. Higher pressures were indicated, but manometers were damaged in these tests. As a rule, the higher the pressure the shorter its duration. Pressures of 50 pounds per square inch or more usually last only a few hundredths of a second.

In weak and slow explosions the most vigorous combustion occurs near the center of the mine passageway, and little or no combustion takes place along the ribs. In the center of the entry in such explosions the oxygen content of the air is frequently reduced to 2 to 3 percent, with production of 10 to 12 percent carbon dioxide and appreciable quantities of carbon monoxide and distillation products from the coal dust. Combustion is more complete in rapid explosions with dry dust, and the oxygen content of the entire body of air may be reduced to below 1 percent; carbon monoxide is frequently present in quantities of 4 percent or more, but the carbon dioxide content is reduced at the same time. This seems to indicate that part of the carbon monoxide is produced by reaction of carbon dioxide with hot carbon after the primary combustion has taken place. In explosions of damp or wet coal dust a water-gas reaction (steam and hot carbon) also seems to take place. This results in formation of hydrogen, methane, and ethane, as well as carbon monoxide and carbon dioxide. After the flame has passed a point, chemical reactions virtually cease,

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and the gases are gradually cooled. However, the remaining gases are not respirable until full ventilation is restored.

Coke found after a coal-dust explosion in a mine is the residue of partly consumed dust. The quantity of coke depends largely on the coking properties of the coal. Slow explosions are favorable to the production of coke, as the dust is exposed to heat for a longer time, and there is less violence tending to destroy masses of coke as they are formed. In appearance the coke may vary from gritty, granular material to bright, shiny sheets from which all volatile matter has been expelled. In general, near the origin of a dust explosion the coke is found facing the source; when the explosion accelerates, coke is more apt to be on the reverse side of timbers or projections; as the explosion dies away it is found on the facing side of projections. Much less coke is found after violent explosions of coal dust, even when the coal has highly coking characteristics.

The forces exerted in violent explosions are very great, and destruction resembles that found after a blast of explosives. In many tests observations were made of the movement of objects whose exact position was known before the explosion. It was noted that movements of considerable magnitude are caused largely by columns of air or burned gases propelled through the entries at high velocities; these pick up and carry objects that sometimes weigh hundreds of pounds. Objects carried by the air blast ahead of the explosion are sometimes overtaken by the flame, which travels at a high velocity and with rising pressure; when the flame passes it, the direction of movement of the objects is reversed, and eventually they may come to rest nearer the origin of the explosion than they were previously. This has happened frequently with fragments of shelving and occasionally with loaded, overturned mine cars. During an explosion, pressure waves emitted by the combustion zone are reflected from the rough walls and closed ends of passageways; their velocities change with temperature, pressure, and movement of gas through which the wave travels. After the explosion ceases there is an inrush of air to fill the partial vacuum created by cooling of the hot gases. This inrush may carry light objects considerable distances, which further complicates the trajectories of objects. All this points to the need for careful study in retracing the paths of a mine-explosion disaster to evaluate the sometimes seemingly contradictory evidences of violence.

REDUCTION IN MINE EXPLOSIONS AND NEED FOR CONTINUED RESEARCH

As a result of research by the Bureau of Mines and by similar organizations in Europe, great strides have been made in our understanding and control of coal-dust explosions. These findings, coupled with increased safety-consciousness in the mining industry and among mine workers, have led to the use of permissible mining equipment, permissible explosives, improved ventilation, improved roof control, and adoption of generalized rock dusting and other recommended practices, with fruitful results. This is evidenced by the decreased severity and frequency of coal-dust explosions throughout the world. In the United States between 1902 and 1911, nearly 350 persons were killed annually by major explosions in coal mines; during 1942 to 1951 the average number killed was about 75 a year (see fig. 6); and during the last 5 years there were 3 major coal-mine explosions, which resulted in 27 fatalities.

In spite of this record, further intensive studies of this problem cannot be and have not been abandoned. Coal-dust explosions are still occurring, and many unsolved problems on this subject remain. This is due in part to their complexity and the many parameters that affect the sensitivity to ignition and the explosibility of coal dust; it must be remembered that only a few laboratories have been studying dust explosions. New problems have arisen owing to changes in mining conditions and

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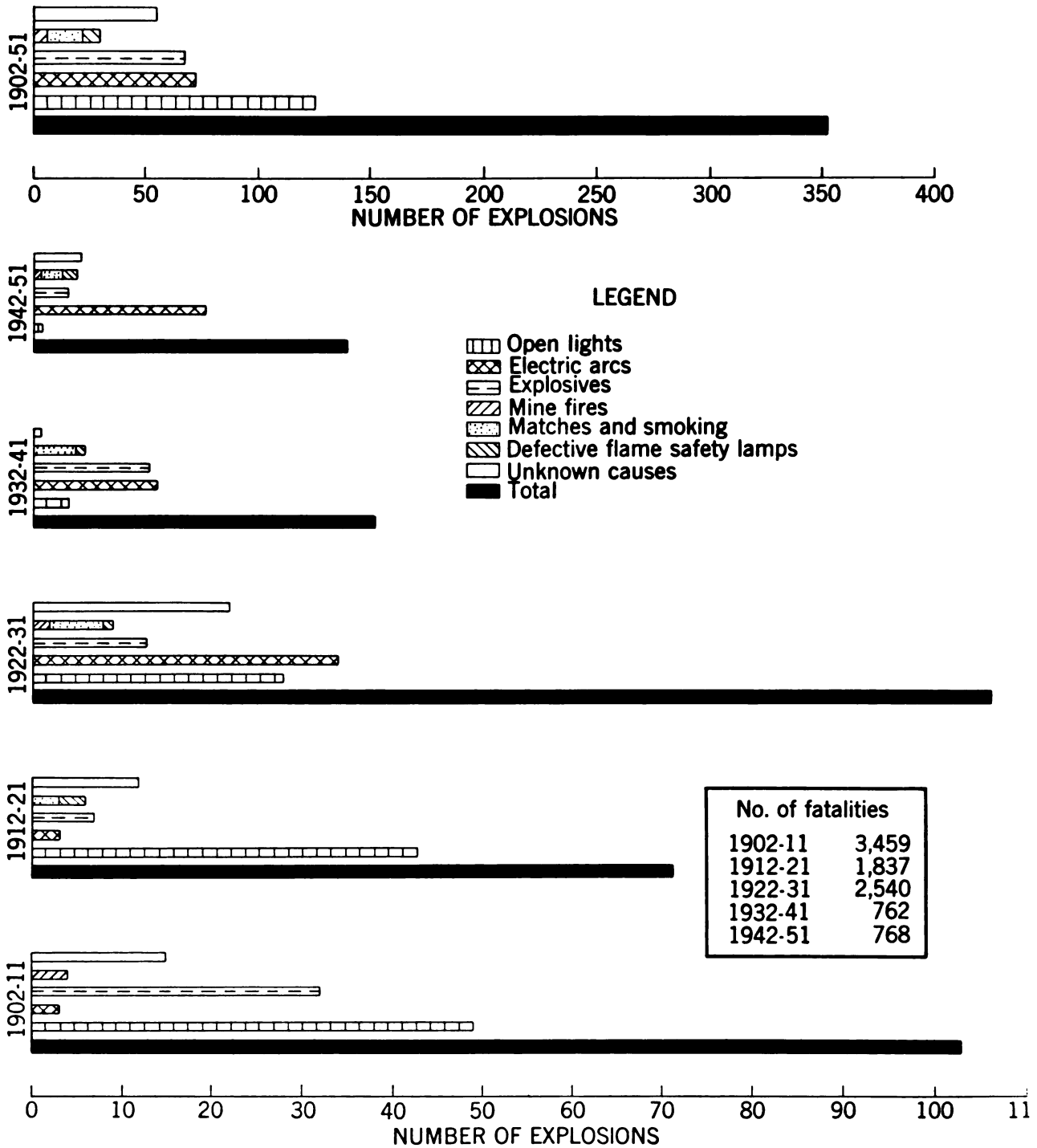

Figure 6. - Causes of major coal-mine explosions in U. S., 1902-51.

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mining techniques; the increased use of pulverized coal in industry; and as a result of enactment of Public Law 552 by the 82d Congress, which imposes on the Bureau of Mines responsibility for preventing major explosions and other major disasters in the Nation's coal mines by inspecting them to detect unsafe conditions. Other research stems from the desire and vital need to improve present measures for controlling explosions; the recognition of limitations of generalized rock dusting; and the need for correcting certain erroneous beliefs (and resulting bad practices) regarding the action of rock dust and the development of coal-dust explosions, by some groups of the mining public.

A potential explosion hazard exists in connection with a number of current and pending applications of pulverized coal in industry. These include pulverized-coal boilers, fluidized fuels, turbines for railroad locomotives, coal gasification, chars of low-rank coals, activated carbons, foundry facings, jet propulsion, synthetic liquid fuels, plastics, chemicals, and the handling of large quantities of coal in thermal drying plants. In some instances the coal dust is normally suspended in air, in oxygen-deficient or oxygen-rich atmospheres, or in other atmospheres.

The problem of dust explosions has been accentuated in modern mechanized mining with high-speed machines, multiple-entry systems, multiple blasting, high-velocity air currents, and rapid haulage. These have resulted in greatly increased production and dissemination of fine coal dust in mine entries. The use of high-speed machines has increased the probability of formation of incendive sparks by frictional contact between moving metals and certain mineral substances in the coal seam, or in the adjoining rock strata. In gassy seams rapid extraction of coal has increased the rate of gas evolution. Difficulties in providing proper roof control in some back entries in the multiple-entry systems have resulted in the spalling of ribs and the production of coal dust in these areas. The use of large mining machines has increased the concentration of electrical power in relatively short sections of mine workings, and these machines have complicated ventilation at coal faces where gas may be given off rapidly. As a result of multiple-shift operation it has become difficult to provide rock-dust protection near rapidly advancing faces. High-speed mining has brought about an excessive accumulation of coal dust and fine coal in some mine workings, including belt-conveyor roads. The removal of coal pillars during retreat mining, particularly the current method of blasting irregular small stumps, produces coal-dust clouds of high concentrations under hazardous conditions. Additional problems arise from economic considerations. An example is the underground storage of coal cuttings, which may have an appreciable combustible content but are not economically marketable.

As is well known, the most practical measure for preventing the propagation of coal-dust explosions in mines is to rock-dust the mine workings. As now practiced, this method is certainly not ideal. The quantity of rock dust required in proportion to the coal dust neutralized is very great; its effectiveness is reduced by fresh deposits of coal dust, which is being produced and disseminated in the mine continuously; frequent re-rock-dusting is needed; and the application is costly. Occasionally difficulties are experienced as a result of caking and loss of dispersibility of rock dust when mine surfaces become moist; and it is difficult to apply rock dust in trackless entries, back entries, and important working areas near rapidly advancing coal faces. Frequently it is troublesome to schedule rock dusting in the mining cycle; during application visibility is reduced, and in some entries the rock dust does not adhere well to rib and roof surfaces. Many small mines cannot afford to purchase rock-dusting machines and must resort to less efficient hand distribution.

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Following passage of The Federal Coal Mine Safety Act (Public Law 552 - 82d Congress), many coal mines were compelled for the first time to start rock dusting and otherwise improve their safety practices. This brought to light lack of understanding of the function of rock dust and the action of coal-dust explosions, which in many instances resulted in failure to apply rock dust properly. It may be useful to cite a few examples of such misconceptions.

It is believed that rock dust is needed only in dry areas of coal mines, because in moist sections the coal dust is harmless, and the rock dust cakes and loses its effectiveness. - It is true that moistened and caked limestone is less dispersible and less effective than dry limestone, and one might wish that more effective measures than rock dusting were available for arresting explosions in moist workings. However, some mine areas become alternately wet and dry many times a year, and it would be wrong to leave them without rock dust. It takes considerably more moisture than mere dampness to prevent the dispersion and explosion of coal dust. Moistened rock dust adheres to and reduces the dispersion of coal dust from mine surfaces, and after partial or complete drying the rock dust regains its dispersibility, at least in part. Thus the conclusion is that application of rock dust in moist places should be continued. If the rock dust has caked, it is advisable that fresh rock dust be applied.

Some believe that rock dusting in mine entries need not be continuous and uniform and that deficiency of incombustible in one place can be compensated by excess rock dust elsewhere in the entry. - In fact, since a coal-dust explosion in a mine is a rapidly moving phenomenon, there can be no compensation for rock-dust deficiency. When the explosion reaches an area that lacks incombustible it is intensified and cannot anticipate rock dust farther along its path.

Abundant "blanket" rock-dust application on the floor of mine entries is thought capable of compensating for complete or partial lack of rock dusting on the rib and roof surfaces in entries. At other mines it is thought sufficient to apply rock dust on the ribs and roof but to leave the floor insufficiently rock-dusted. - Tests have shown that whereas, under certain conditions, a small deficiency of rock dust on the floor can be compensated by excess rock dust on the rib and roof surfaces, the reverse cannot be accomplished. The practice of blanket rock dusting at the expense of adequate rock-dust application on overhead surfaces can result in the development of widespread explosions.

The requirement to apply rock dust to within 40 feet of coal faces is often considered too restrictive, and it is thought that application to within a few hundred feet of the face gives adequate protection. - Actually, experiments indicate that explosions that are permitted to develop for such distances before entering rock-dusted zones might become very violent and propagate for nearly 1,000 feet or more through the rock-dusted zone.

"Dustless" zones in entries are thought to be effective in stopping explosions. - However, no part of an entry in an operating coal mine can be maintained entirely free of coal dust. Furthermore, tests have shown that strong explosions can readily propagate through several hundred feet of nearly dust-free entries.

A coal-dust explosion that originates in a short non-rock-dusted area is often believed to be stopped instantly or within a very short distance after it reaches a rock-dusted section. - However, such explosions cannot be quenched immediately but will propagate from 100 to several hundred feet through the rock-dusted zone before the flame is extinguished.

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The requirement of 65 percent incombustible in mine dust is thought to provide a considerable factor of safety against coal-dust explosions. - This value, based on numerous explosion tests, represents a minimum standard for bituminous-coal mines. It gives no guarantee that an explosion will never occur, but it does give assurance that if the rock dust has been properly applied and maintained, widespread explosions will not develop.

RECENT AND CURRENT RESEARCH PROBLEMS

To solve the technical problems arising from the Bureau's coal-mine-inspection activities, to keep abreast of rapid advances in mining mechanization, and to gain a better insight into the causes and mechanism of coal-mine explosions, many projects have been explored recently at the Experimental Coal Mine, in the associated laboratories, and in the field. A partial list of these investigations, with brief résumés, follows:

(1) Experiments on Short-Delay Blasting of Coal[2/]

To determine what hazards exist in short-delay blasting and to compare these with single and with simultaneous multiple blasting, 264 large-scale tests were made in the Experimental Coal Mine. Attention was given to the ignition hazards of gas and coal dust, effects on mine roof, quantity and breakage of coal produced, amount of float dust formed, relative time requirements for blasting, and the problem of misfires. The studies suggest that short-delay multiple blasting in coal with permissible explosives can be accomplished as safely as single-shot blasting when the operation is carried out as recommended by the Bureau of Mines. However, this does not constitute official sanction of the practice by the Bureau.

(2) Ignition of Coal Dust by Permissible Explosives[3/]

The purpose of this research was to study the conditions under which coal dust can be ignited by permissible explosives and to determine how such ignitions can be prevented in coal mines. More than 300 experiments were performed with 14 brands of permissible explosives and with 3 nonpermissibles. The experiments showed that conditions under which permissible explosives can ignite coal dust are much more restricted than conditions for ignition of gas; the presence of a few percent of natural gas in the atmosphere was found to enhance the ignitibility of coal dust. It was found that permissible explosives fired in short holes in coal according to the procedure recommended by the Bureau of Mines will not ignite coal-dust layers or coal-dust clouds in air. The principal recommendations specify a limited charge weight per shot hole; undercutting and other relief of the coal face; a minimum depth of coal burden surrounding the shot hole; and provision of adequate incombustible stemming or an approved stemming device in the shot hole.

2/ Hartmann, Irving, Nagy, J., and Howarth, H. C., Experiments on Multiple Short-Delay Blasting of Coal - Part I: Bureau of Mines Rept. of Investigations 4868, 1952, 16 pp.
Nagy, J., Hartmann, Irving, Christofel, F. P., and Seiler, E. C., Experiments on Multiple Short-Delay Blasting of Coal - Part II: Bureau of Mines Rept. of Investigations 4875, 1952, 22 pp.
Hartmann, Irving, and Lewis, B., Experiments on Short-Delay Blasting in the Experimental Coal Mine: Bureau of Mines Rept. of Investigations 5026, 1954, 6 pp.

3/ Hartmann, Irving, Nagy, J., McGibbeny, E. B., and Christofel, F. P., Ignition of Coal Dust by Permissible Explosives: Bureau of Mines Rept. of Investigations 4873, 1952, 18 pp.

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(3) Laboratory Explosibility Study of American Coals[4/]

This study was made to obtain data on the explosive characteristics of dusts of several ranks of coal, ranging from lignite to meta-anthracite (range of volatile ratios, approximately 50 to 4.5). Determinations were made of the ignition temperature, relative flammability, lower explosive limit, minimum igniting energy, and maximum explosion pressures and rates of pressure rise developed in experimental dust explosions. The effects of volatile matter, particle-size distribution, moisture content, dust concentration, and oxygen content in the atmosphere were studied.

(4) Hazards of Underground Storage of Coal Cuttings[5/]

In some mines it is not economically feasible to load and remove cuttings from the mine. In such instances the cuttings are sometimes stored in random heaps in rooms or other areas, along the ribs of mine entries, or in layers on the floor of workings. Tests were made in the Experimental Coal Mine to determine the potential explosion hazards due to the presence of cuttings and to investigate whether any practical measures can be taken to lessen the hazard. The study showed that the presence of coal cuttings underground may well enhance the propagation of coal-mine explosions. The hazard can be reduced by eliminating irregularities in the stored material and by leveling the surface to provide the smallest area on which the forces of an explosion can act. The surface should then be covered with a thick layer (preferably 1 inch or more) of limestone (see fig. 7), or if desired the surface can be consolidated into a firm covering. In addition, coal dust on the rib and roof surfaces must be neutralized by generalized rock dusting.

(5) Effect of Loaded Mine Cars on Propagation of Explosions[5/]

Investigation following a recent widespread explosion disclosed that the presence of several trips of mine cars may have contributed to the propagation of flame. The cars had been loaded (topped) on the previous day with friable coal produced at the mine to a height 10 inches above the level of the car frame and were left standing in the entry. The coal contains about 20 percent of particles smaller than 1/4 inch and an appreciable quantity of fine dust capable of supporting an explosion. As this manner of loading cars and scheduling their haulage is standard practice in many mines, about 20 explosion tests were performed in the Experimental Coal Mine to study the problem. The investigation has shown that mine cars filled with coal cuttings or similar fine coal produced by continuous mining operations, when parked in the mine entry in the path of an explosion, may, under some conditions, greatly increase the length of flame travel, even though the entries are properly rock-dusted. The principal effect appears to be due to combustion of fine coal particles that are eroded from the tops of the cars by the pressure wave preceding the explosion flame. The experiments indicate the need for safeguards, in addition to adequate generalized rock dusting of the entries. Possible safeguards include: (1) Light overhead cross shelves with rock dust in the area and for a short distance inby and outby the area where the loaded cars are parked (see fig. 8); (2) loading the top part of cars that contain coal cuttings and other fine coal, with coarse run-of-mine coal; and (3) providing an incombustible covering over the cars that are loaded and topped with fine coal.

4/ Hartmann, Irving, Jacobson, M., and Williams, R. P., Laboratory Explosibility Study of American Coals: Bureau of Mines Rept. of Investigations 5052, 1954, 8 pp.

5/ Hartmann, Irving, Nagy, J., Rauschenberger, J. K., and Mitchell, D. W., Coal-Mine-Explosion Research by the Bureau of Mines, 1954-55: Bureau of Mines Rept. of Investigations 5264, 1956, 26 pp.

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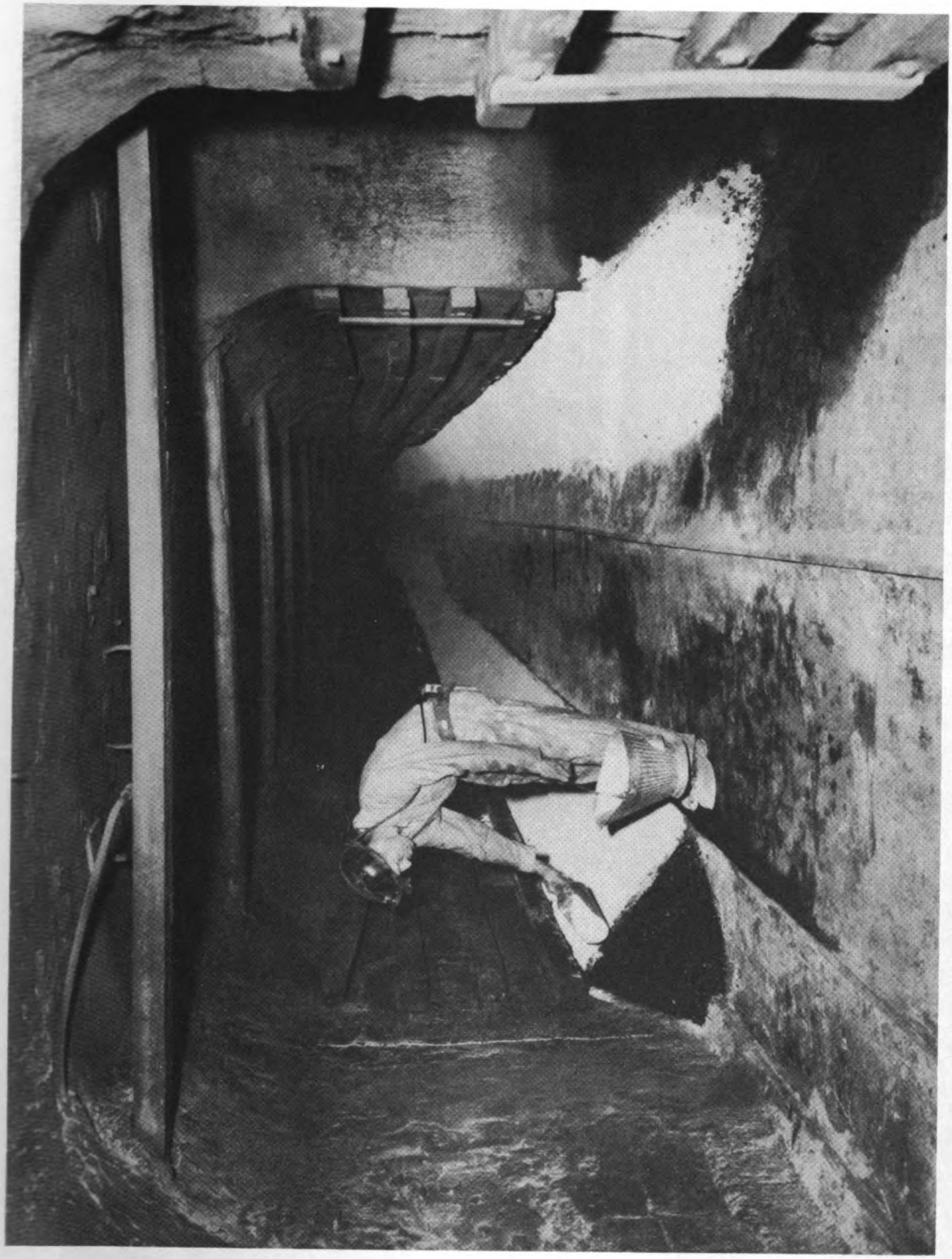

Figure 7. - Coal cuttings banked against ribs of mine entry being covered with limestone before explosion test.

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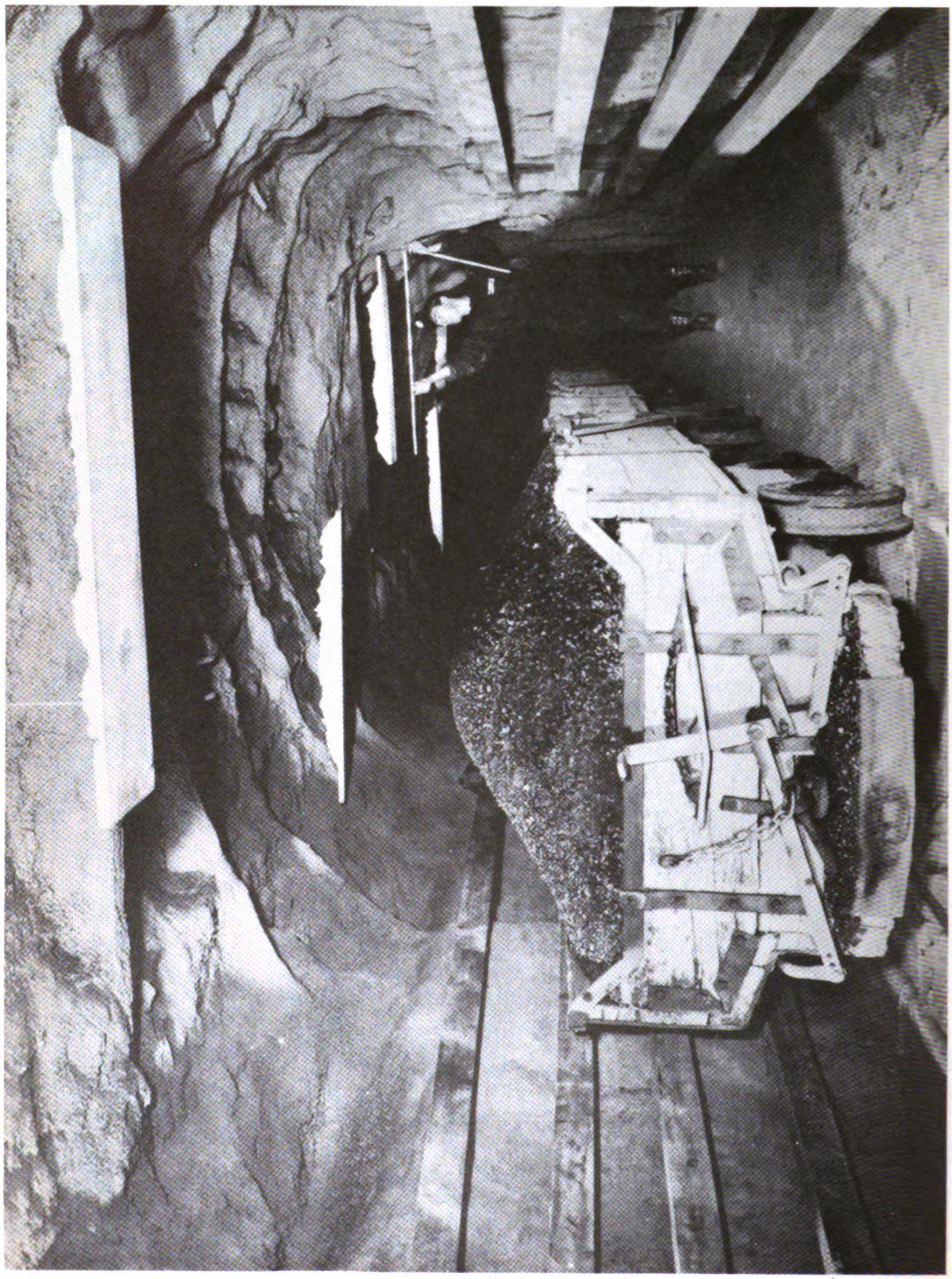

Figure 8. - Mine cars loaded with cuttings in entry beneath suspended rock-dust shelves before explosion test.

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(6) Effect of Excessive Accumulation of Coal Dust and Fine Coal in Mine Entries

More than 20 explosion tests were made in the Experimental Coal Mine, in which 2, 4, or 6 heaped deposits (generally 300 pounds each) of coal dust or coal cuttings in the form of prismoids, with a base of 4-1/2 by 3-1/2 feet and a height of 2 feet, were placed slightly off the center line of the entry. The deposits were generally spaced equally within a 100-foot zone. The explosions were initiated by 1 of 4 types of sources; these included a gas-air mixture and blown-out shots fired into pure coal-dust zones of various lengths. Outby the ignition zone the entry contained mixtures of coal dust and limestone with enough incombustible to prevent propagation of an explosion, neglecting the additional heaped deposits of coal. The experiments showed that the presence of the heaped (excessive) deposits of coal dust or cuttings enhanced the travel of flame, in some instances by as much as 350 feet. The explosions with deposits of fine coal were more severe than those with cuttings. The closer the deposits were to the igniting source the greater was the flame extension; length of flame was not increased appreciably when the deposits were placed in the outer end of the zone where the flame normally stopped. To study the alleviation of the hazard of excessive dust deposits, in several tests the top of the coal dust was covered with a 1-inch layer of limestone dust. This was effective in reducing the added hazard of the piles of coal dust. Explosion and post-explosion effects caused the deposits to assume pancakelike shapes averaging 7 feet in diameter and 1/2 foot in height.

(7) Effect of Moisture on Explosibility of Coal Dust

Mention has already been made of limited large-scale tests in the Experimental Coal Mine on this problem with Pittsburgh-bed coal dust (see fig. 5). To confirm and to extend the information, laboratory experiments are in progress with coal dusts of various ranks and particle sizes. In these tests there is determined the proportion of inert (limestone) dust required in mixture with the coal dust, to prevent ignition and flame propagation when the mixture is dispersed through a laboratory furnace heated to a preset standard temperature. Preliminary data indicate that the inhibiting and inerting effect of moisture is considerably greater, especially for the coarser coal dusts, than the effect of solid incombustible in the dust mixture.

(8) Fire and Explosion Hazards in Thermal Coal-Drying Plants[6/]

This was chiefly a field project started after a severe explosion in a coal-drying plant. The purpose of the study was to obtain information considered essential for properly appraising fire and explosion hazards in different types of coal driers.

(9) Water Infusion for Suppressing Formation of Coal Dust

Experience in Australian and European coal fields has shown that injection of water into the coal seam before mining has been effective in many instances in reducing the quantity of fine coal dust produced during the mining process. A limited number of tests were made in the Experimental Coal Mine to evaluate the effect of water infusion on dust produced during mining in the Pittsburgh coal seam. Water was forced into boreholes 6 to 20 feet in depth, at pressures ranging from 18 to 100

6/ Brown, H. R., Dalzell, C. J., Hartmann, Irving, Toothman, G. J. R., and Schwartz, C. H., Fire and Explosion Hazards in Thermal Coal-Drying Plants: Bureau of Mines Rept. of Investigations 5198, 1956, 20 pp.

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pounds per square inch. Samples of airborne dust were collected with a midget impinger during undercutting, drilling, blasting, and loading in 12-foot-wide rooms. The results showed wide variations in the amount of dust produced in repetitive tests under identical conditions, which masked the effect, if any, of water infusion. Although no precise conclusions could be drawn from the test results, it is apparent that infusing water into the Pittsburgh coal seam has little if any beneficial effect on reduction of dust.

(10) Lessons From Intensive Dust Sampling of a Coal Mine[7/]

This investigation was based chiefly on a comprehensive dust-sampling survey in a commercial coal mine. Its purpose was to obtain some much needed information on the adequacy of current rock-dusting and dust-sampling practices in coal mines. More immediate aims of the work were to determine the variations of incombustible content in mine dust on the floor and on rib-roof surfaces along mine entries, secondary entries, and rooms; to compare spot or grab samples with concurrent strip samples; to determine the amount and fineness of dust in entries; to examine the nature of the solid incombustible in mine dusts; and to check underground the usefulness of a rapid, approximate color-sorting procedure for separating dusts of high and low incombustible content. On the basis of the study in this mine it was concluded that: (1) Band or perimeter sampling of dust can be substituted with no sacrifice in safety, for the more time-consuming road and rib-roof sampling; (2) the incombustible in the top 1-inch layer of dust on roadways gives a good estimate of the incombustible in the full-depth dust deposit; (3) the incombustible in many mine dusts contains large portions of sand, shale, or other coarse material much less effective in stopping explosions than normal, finely divided limestone dust. Since conclusion of this investigation it has been found, as already indicated, that in many coal mines rock dust is spread on the floor, but little or no rock dust is applied to the ribs and roof and vice versa. For this reason, serious consideration is being given to resumption of the collection of separate road and rib-roof samples.

(11) Rock-Dust Requirements for Floor and Rib-Roof Surfaces of Mines[8/]

This investigation showed that deficiency of rock dust on the floor of mine workings can, within certain limits, be compensated by excess rock dust on rib-roof surfaces, so that the weighted incombustible content of the total dust around the perimeter of an entry is maintained at 65 percent. The limits depend on the strength of a potential explosion and on distribution of the dust on the floor and overhead. The tests also showed that deficiency of rock dust on rib-roof surfaces cannot be compensated by applying excess rock dust on the floor.

(12) "Blanket" Rock Dusting on Floor of Entries[9/]

Mention has already been made of the practice in some mines of applying an abundant "blanket" rock-dust layer on the floor of entries and neglecting rock-dust application on rib and roof surfaces. This is done partly because it is easier to spread rock dust on the floor than on overhead surfaces and partly because of the

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7/ Hartmann, Irving, Nagy, J., and Rauschenberger, J. K., Lessons From Intensive Dust Sampling of a Coal Mine: Bureau of Mines Rept. of Investigations 5054, 1954, 12 pp.

8/ Hartmann, Irving, Nagy, J., and Christofel, F. P., Incombustible Required on Floor and on Rib-Roof Surfaces of Coal Mines to Prevent Propagation of Explosions: Bureau of Mines Rept. of Investigations 5053, 1954, 7 pp.

9/ Work cited in footnote 5, p. 18.

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belief of some that excess rock dust on the floor will compensate for deficiency of rock dust overhead. A limited investigation was made in the Experimental Coal Mine to test this theory. The experiments showed that blanket rock dusting of the floor is not effective in stopping explosions. In the tests only a small proportion of the limestone dust was raised off the floor during an explosion, although pressures as high as 40 pounds per square inch were developed in the tests. These tests, and the results of the foregoing investigation, show clearly that application of rock dust on the floor alone, even in excessive quantities, cannot compensate for deficiency of rock dust on the ribs and roof.

(13) Promoting Adherence of Rock Dust to Mine Surfaces[10/]

Frequently, difficulties are experienced during application of rock dust with machines owing to inadequate adherence of the dust to the ribs and roof of entries, particularly when the surfaces are dry and smooth. In a number of controlled tests in the Experimental Coal Mine it was found that, even with good adherence, not more than 30 to 35 percent of the limestone dust applied with machines sticks to the ribs and roof; the balance falls on the floor, and some is carried away by the air current. This poor adherence is sometimes given as a reason for lack of rock dust on overhead surfaces. Various experiments were performed in attempts to improve adherence of rock dust to the ribs and roof of mine entries. The study indicates that slight moistening of rib and roof surfaces shortly before, or simultaneously with, the application of rock dust is sometimes highly effective in improving adherence of the rock dust.

(14) Distribution of Rock Dust by Permissible Explosives[11/]

Tests were made in the Experimental Coal Mine to determine whether rock dust can be distributed effectively with permissible explosives and to ascertain whether explosive gas-air mixtures or coal dust might be ignited during the process. In one method under study a stick of explosive was placed on the floor of a room or entry, midway between the ribs, and covered with two bags of rock dust that were slit on top and set crosswise one above the other. The explosive was then fired, causing the rock dust to be distributed on the nearby rib-roof and floor surfaces. The procedure was repeated at desired intervals until the area was rock-dusted. The study showed that, under properly controlled conditions, bags of rock dust can be dispersed by permissible explosives without igniting gas or coal dust. It also showed that improper placement of the explosive and bags may result in ignitions of gas. This method is not recommended officially by the Bureau of Mines.

(15) Bag-Type Rock-Dust Devices for Limiting Propagation of Explosions[11 12/]

To protect trackless entries and other areas where it is difficult to maintain generalized rock dusting, bag-type rock-dust devices have been used in a few coal

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10/ Work cited in footnote 5, p. 18.

11/ Hartmann, Irving, Nagy, J., Howarth, H. C., and Sachs, A., Recent Rock-Dusting Experiments for Arresting Coal-Mine Explosions: Bureau of Mines Rept. of Investigations 4688, 1950, 16 pp.

12/ Greenwald, H. P., and Howarth, H. C., Tests of a Barrier Using Rock Dust in Paper Bags: Bureau of Mines Rept. of Investigations 3411, 1938, 16 pp.
Howarth, H. C., Nagy, J., Hartmann, Irving, Greenwald, H. P., and Lewis, B., Tests in the Experimental Coal Mine to Determine Requirements for Preventing Propagation of Coal-Dust Explosions in Rooms: Bureau of Mines Rept. of Investigations 4195, 1948, 12 pp.
Results of experiments on most recent modifications of the bag-type devices will be described in a forthcoming Bureau of Mines report.

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mines. Advantages claimed for these devices include the following: (1) They afford good supplementary protection in back entries; (2) they provide added protection against fresh deposits of coal dust; (3) they can be installed easily and quickly on shift, with little discomfort in breathing; (4) they make rock dust readily available for fire fighting; (5) the rock dust does not become wet from contact with moisture on mine surfaces; (6) the rock dust is not covered by spalled roof rocks as readily as is generalized rock dusting; and (7) the bag-type installation can easily follow rapid advance of the coal face. Tests with various modifications of these devices showed that one of their drawbacks was inadequate dispersion of the rock dust into the air stream at the proper moment. To overcome this a burster, consisting of a charge of permissible explosive, was incorporated in the bag-type units. In a few tests the explosive charges were triggered by a manually timed switch; in others a pressure-sensitive or a flame-sensitive device was operated by the explosion itself. The tests indicated that a properly designed system of bag-type units, equipped with bursters for dispersing the dust, was capable of arresting coal-dust explosions. However, much additional development work is needed before such devices can be considered for installation in commercial mines.

(16) Wet Rock Dusting As an Explosion-Prevention Measure[13/]

In mechanized mines where continuous miners are used on three shifts, a working face may advance several hundred feet daily. To comply with the requirement that rock dust be applied to within 40 feet of all active faces, rock dusting would have to be performed during the working shift. Conventional rock dusting with machines is a very dusty operation, and it is difficult to apply rock dust in this manner near active faces. Dense dust clouds reduce visibility and constitute a nuisance and a health hazard, and the dust may impair expensive mining machines. To correct this condition various temporary substitute measures for rock dusting have been studied. One procedure consists of applying wet rock dust either in the form of a premixed slurry or by mixing rock dust with water at the nozzle of a rock-dusting machine (see fig. 9). The assumption is that, after evaporation of the water, the rock dust will regain its dispersibility, at least in part.

Recently an extensive investigation was carried out in the Experimental Coal Mine to determine the applicability and limitations of wet rock dusting and to evaluate its effectiveness in preventing propagation of large coal-dust explosions. The tests showed that protection against explosions near rapidly advancing coal faces can be achieved without undue difficulties by applying wet rock dust on rib and roof surfaces and by applying dry rock dust on the floor of mine entries to neutralize the coal dust thereon. After wet rock dust has been applied a close check should be maintained in the treated entries to observe when the wetted dust, after drying, begins to spall off the rib and roof surfaces appreciably. This indicates that fresh rock dust should be applied. It should also be observed whether and at what rate fresh (float) coal dust is deposited on the surfaces, so that fresh rock dust can be applied before enough float dust accumulates to produce an explosive dust concentration if the dust is thrown into suspension.

13/ Hartmann, Irving, and Westfield, J., Rock Dusting and Sampling, Including Wet Rock Dusting, at the Bureau of Mines Experimental Coal Mine: Bureau of Mines Inf. Circ. 7755, 1956, 13 pp.
Hartmann, Irving, and Nagy, J., Effectiveness of Wet Rock Dusting as an Explosion Prevention Measure: Trans. Nat. Safety Council, vol. 5, 1955, pp. 19-23.
Hartmann, Irving, and Nagy, J., Explosion Prevention by Wet Rock Dusting: Mechanization, vol. 20, No. 1, 1956, pp. 73-76.
Work cited in footnote 5, p. 18.

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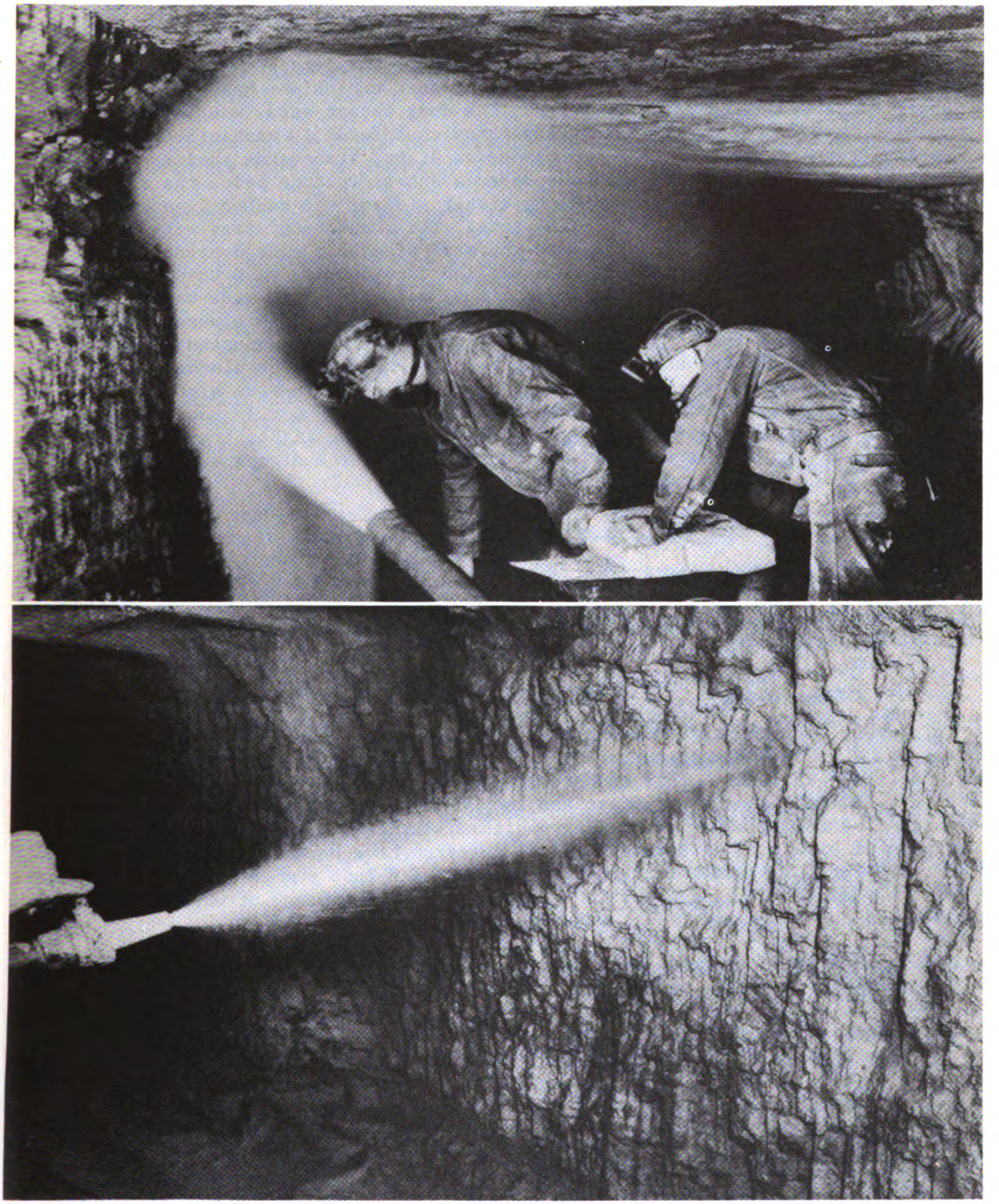

Figure 9. - Rock-dust application in Experimental Coal Mine.
Upper: Conventional (dry) rock dusting.
Lower: Application of limestone-water slurry.

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(17) Water Barriers and Rock-Dust Barriers

The effectiveness of numerous types of rock-dust barriers and of several types of water barriers for stopping experimental coal-dust explosions has been studied in the Experimental Coal Mine for many years. The most recent study was made in connection with the protection of rapidly advancing coal faces in mechanized mining.14/ In 1 series of tests the rock dust was placed on light, transverse shelves 4 feet long and 10 inches wide. These were suspended a short distance below the roof and set 5 feet apart in 2 staggered rows along either side of the center line of the entry. Each board held 10 pounds of limestone. The suspension wires were readily broken by the pressure wave that preceded the explosions, and the contents of the boards were dispersed into the air. Water-filled troughs were used to control the explosion in a few other tests. The troughs were made of 8-inch-wide boards, 4 feet long, set 10 feet apart in 2 staggered rows along the entry. There were 30 troughs in the test zone; each held 10.5 gallons of water. They were supported below the roof on 3/4-inch round iron shafts. To control the rate of water discharge, the top of every other trough was partly covered to provide a 1/2-inch-wide slot at each end. Uncovered troughs discharged the water in 1 second and partly covered troughs in about 3 to 4 seconds. The investigation showed that the light, transverse rock-dust shelves and the water troughs installed near the source of the explosions were highly successful in arresting flame propagation.

(18) Transport of Dust by the Air Current

An investigation has been initiated recently to study the parameters governing the rate of transport of coal dust and other mine dusts by the ventilating current and dust deposition on the entry surfaces. No conclusions have been reached on the basis of the work to date.

(19) Recent Research in European Countries

Interchange of information on mine-safety-research problems between the Bureau of Mines and a number of Western European mining experiment stations has been in effect for about 25 years. This cooperation resulted in a large measure from the desire to avoid duplication of effort and to promote progress in the study of coal-mine explosions and of other mine safety matters. Since 1931 nine International Conferences of Directors of Safety in Mines Research have been held in this country and abroad. The 9th International Conference was held last summer in the Netherlands and Belgium. At the technical sessions on coal-dust explosions, of which the writer was chairman, the following papers were presented:

(1) The Relative Ignition Risk of Coal-Dust Clouds by Permitted Explosives, by H. C. Grimshaw (Great Britain).

(2) Research on the Safety of Explosives From the Standpoint of Ignition of Coal-Dust Layers, by W. Cybulski (Poland).

(3) Effect of Petrographic Properties on the Explosibility of Coal Dust, by H. Hanel (East Germany).

14/ Hartmann, Irving and Nagy, J., Explosion Prevention by Wet Rock Dusting and Other Measures Near Rapidly Advancing Coal Faces: Proc. 69th Annual Meeting, Coal Mining Inst. America, Pittsburgh, Pa., 1955 (in press).

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(4) Explosion Hazards From Localized Deposits of Coal Dust, by S. K. Shaw and D. W. Woodhead (Great Britain).

(5) Coal-Dust Explosion Problems in Belt-Conveyor Roads, by W. Cybulski (Poland).

(6) Research on the Explosion Hazard of Separated Layers of Coal Dust and Rock Dust, by W. Cybulski (Poland).

(7) Coal-Mine-Explosion Research by the Bureau of Mines, 1954-55:

1. Underground Storage of Coal Cuttings.
2. Thick "Blanket" Rock Dusting on Floor of Entries.
3. Adherence of Rock Dust to Rib and Roof Surfaces.
4. Wet Rock Dusting Near Rapidly Advancing Coal Faces.
5. Effect of Loaded Mine Cars in Entries on Propagation of Explosions.

By Irving Hartmann, J. Nagy, J. K. Rauschenberger, and D. W. Mitchell (United States).
(Published as Bureau of Mines Rept. of Investigations 5264, 1956, 26 pp.)

(8) Recent Studies on the Practical Application and Scientific Investigations of the Salt Processes in Germany, by H. Schultze-Rhonhof (West Germany).
(Development and experiments in Germany with the (sodium chloride) salt-crust process and the calcium chloride paste process for controlling mine explosions are described.)

(9) Tests on Rupture Disks and a Spring-Loaded Valve for Explosion Venting, by W. Maas and P. Quaden (Netherlands).

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